Part VI

Stellar Astronomy and Astrophysics

Chapter 17

Binary Stars

Five (5) Reasons Why the Most Interesting, Most Exciting, & Most Important Objects to Observe (Interferometrically or Otherwise) are Binary Stars

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These course notes are primarily concerned with answering five of the six standard "reporter's questions"—the Who, What, Where, When, and How of the field. In this Chapter we're attempting to answer the last of the questions—the "Why." Hal McAlister, in Chapter 1, discussed some of the whys, but it's worthwhile to repeat and expand upon some of the topics he discussed. After all, the most important aspect of this field isn't the great hardware or clever software being developed; in the end it's the science which will come out of it.

My title is rather tongue in cheek, but I hope to convince you that the study of binary stars is indeed an important and worthwhile topic. I might note that binary stars may be considered the reason behind the existence of CHARA and the CHARA Array. Hal McAlister became involved in the study of binary stars using the technique of speckle interferometry in the mid-1970s. The success of this speckle effort led to the creation of the CHARA research group and later to dreams of higher resolution; it also gave CHARA the credentials to raise the money for its array project. The goals of the CHARA Array go far beyond just binary stars, of course, but they are an important part of its history (and future).

So, what are the five reasons? (Let me note that at no time do I say these are the *only* five reasons!) Much of what I discuss will be familiar, but I want to remind you of these topics and give examples of the contribution interferometry can make to each.

17.1 Reason One: Binaries as Scales

This is arguably the most important reason, since mass is **the** fundamental quantity which determines a star's luminosity, size, lifetime, heavy-element generation, and ultimate fate. However, you cannot determine the mass of a single star any more than you can directly measure your weight without the use of bathroom scales or some other means of measuring the gravitational force you exert. To determine stellar masses, then, we need to derive the orbital motions of binary stars.

But why is interferometry important in binary star work? The answer is a two-parter:

17.1.1 Part 1

No single technique for studying binary star orbits gives us all the information we need. For example, an astrometric or "visual" orbit (I will use these terms interchangeably) yields the elements P, a'', T, and e which define the size and shape of the orbit and the rate of motion of the stars, plus the three angles i, Ω, and ω which define the orientation of the orbit in space. However, Kepler's Third Law requires the linear separation a between the stars, rather than the angular separation.

On the other hand, a spectroscopic orbit yields P and $a \sin i$ ($a_1 \sin i$ and $a_2 \sin i$ if it's a double-lined spectroscopic binary, or SB2). We now get the linear separation, but convolved with the inclination.

We therefore need to gather data by at least two complementary techniques. For example, distance + astrometric orbit yields a, thus the mass sum. More on this combination later. A particularly useful combination is spectroscopic + astrometric data, which (if SB2) will give us individual masses.

17.1.2 Part 2

Different observing techniques are applicable in different separation or period regimes. Consider the two techniques just discussed:

- Astrometric observations—measuring separations and position angles—require binaries which are wide enough to be seen as separate images. This means wide, mostly long-period systems.
- Spectroscopic observations—measuring Doppler shifts of spectral lines—requires radial velocities high enough to noticeably move those spectral lines. This means close, short-period systems.

The histogram in Figure 17.1 illustrates the problem. Here I have tallied orbits from the spectroscopic orbit catalogue of Batten *et al.* (1978; data from Griffin 1992), as well as orbits

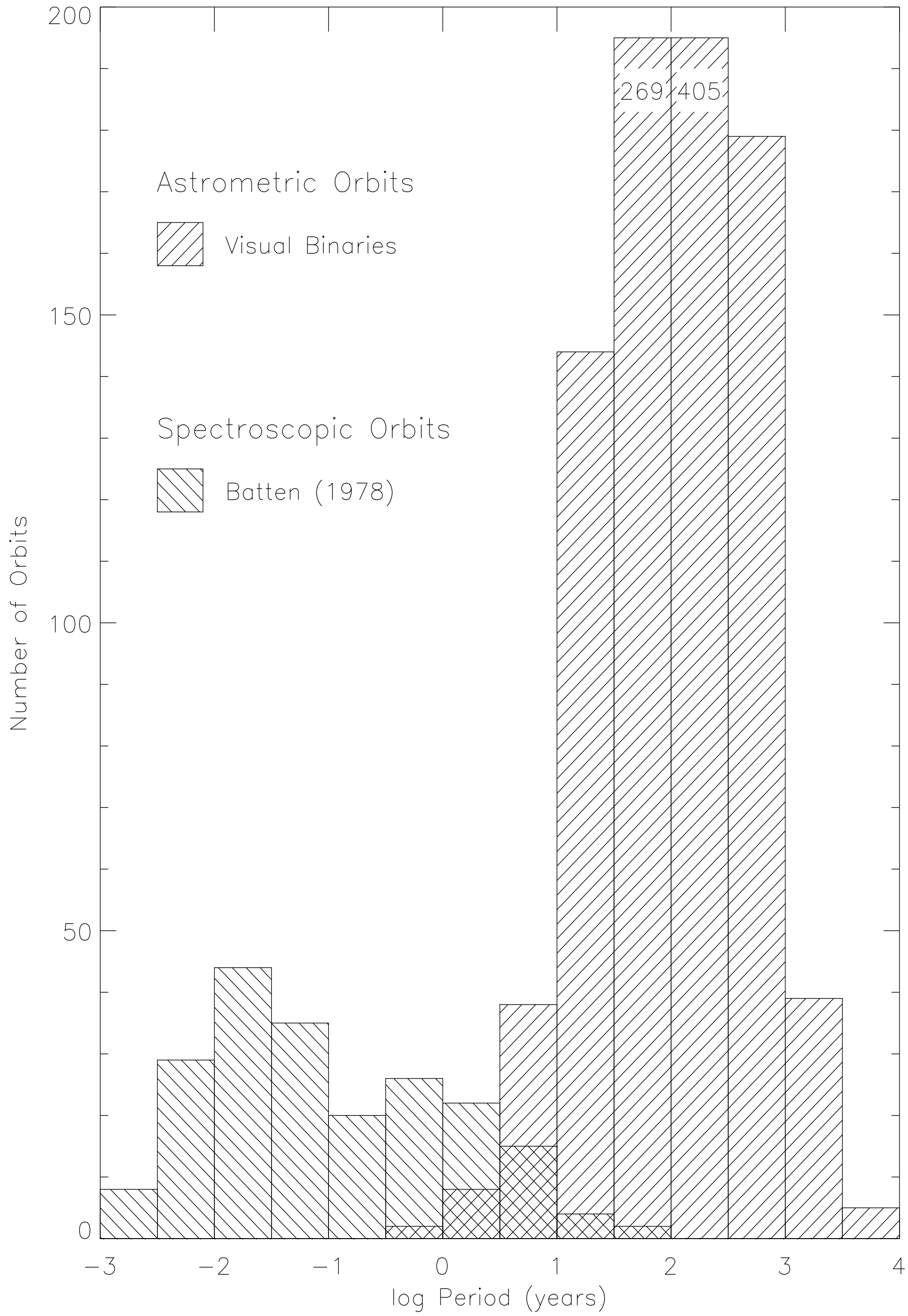

Figure 17.1: Published binary star orbits, binned by period. Shown here are spectroscopic orbits from Batten *et al.* (1978, poorer quality orbits removed), as well as astrometric orbits of all visual binaries in the USNO orbit database. Two columns of visual orbits were truncated for display purposes; the numbers near the top of these columns indicate the true number of published orbits in these period ranges.

of visual binaries from the current catalogue maintained at the USNO. (Note: the poorer quality Batten orbits—grades 4 and 5—have been removed from this histogram. Poorer quality visual orbits have not been removed, however, as most of these orbits have not yet been graded. The poor orbits are generally for systems with extremely long periods—centuries or longer—so their coverages are incomplete.)

We see little overlap. Of course, even this overlap is misleading, since these are not all stars in common to both lists. Dimitri Pourbaix (1998) searched the literature for visual binaries which were also double-lined spectroscopic systems. His results: there are some 500 SB2s with orbits (many very poor), but only 174 of these with astrometry as well and only 38 with sufficient astrometry for a combined solution. Think of the overlap region, then, as illustrating the upper limit to the number of possible combined-solution systems.

Improvements in spectroscopic equipment and reduction techniques (coravel, other cross-correlation methods) have enabled spectroscopists to measure much smaller velocity shifts, thus longer-period systems. In Figure 17.2, I include orbits derived by Roger Griffin using his cross-correlation technique. This collection is as of 1992, so matters have improved a bit over what is shown here. There is a limit, however! As Griffin (1992) has pointed out, in order for spectroscopists to increase their overlap with visual orbits significantly they must observe objects for a century or more. However, Roger says he plans to be doing other things by then! Most of the improvement must come from the "visual" side—this is where interferometry can make its mark.

Speckle interferometry has been in routine use for about 25 years now, discovering new systems with separations down to a few tens of milliarcseconds (corresponding to periods in the years to decades range). The Mark III did a bit better (periods of weeks to years), although for a small number of stars and over a shorter period of time, and NPOI is beginning to obtain data for much closer systems (periods of days). Orbits of binaries discovered by interferometric techniques have also been added to Figure 17.2. The overlap has improved, but there is still a long way to go. This is where some of the array projects you have seen or heard discussed this week come in. Arrays such as NPOI and CHARA have the capability of resolving essentially all of these SBs (at least of those visible to northern observers). I must stress that the reason for making these observations is not to just create a fat catalog of stellar masses, however! Figure 17.3 shows a mass-luminosity plot (Mason, private communication) for binaries whose masses were derived from speckle orbits. Note the lack of coverage, especially at the low- and high-mass ends. The number of masses known to even 5% accuracy is too small to accurately define the M-L relation for "typical" solar-neighborhood main-sequence stars, let alone see how that relation is effected by, say, metallicity, age, etc. Such knowledge would be of great importance to stellar evolution theorists.

So masses are an obvious reason to study binaries. This brings us to ...

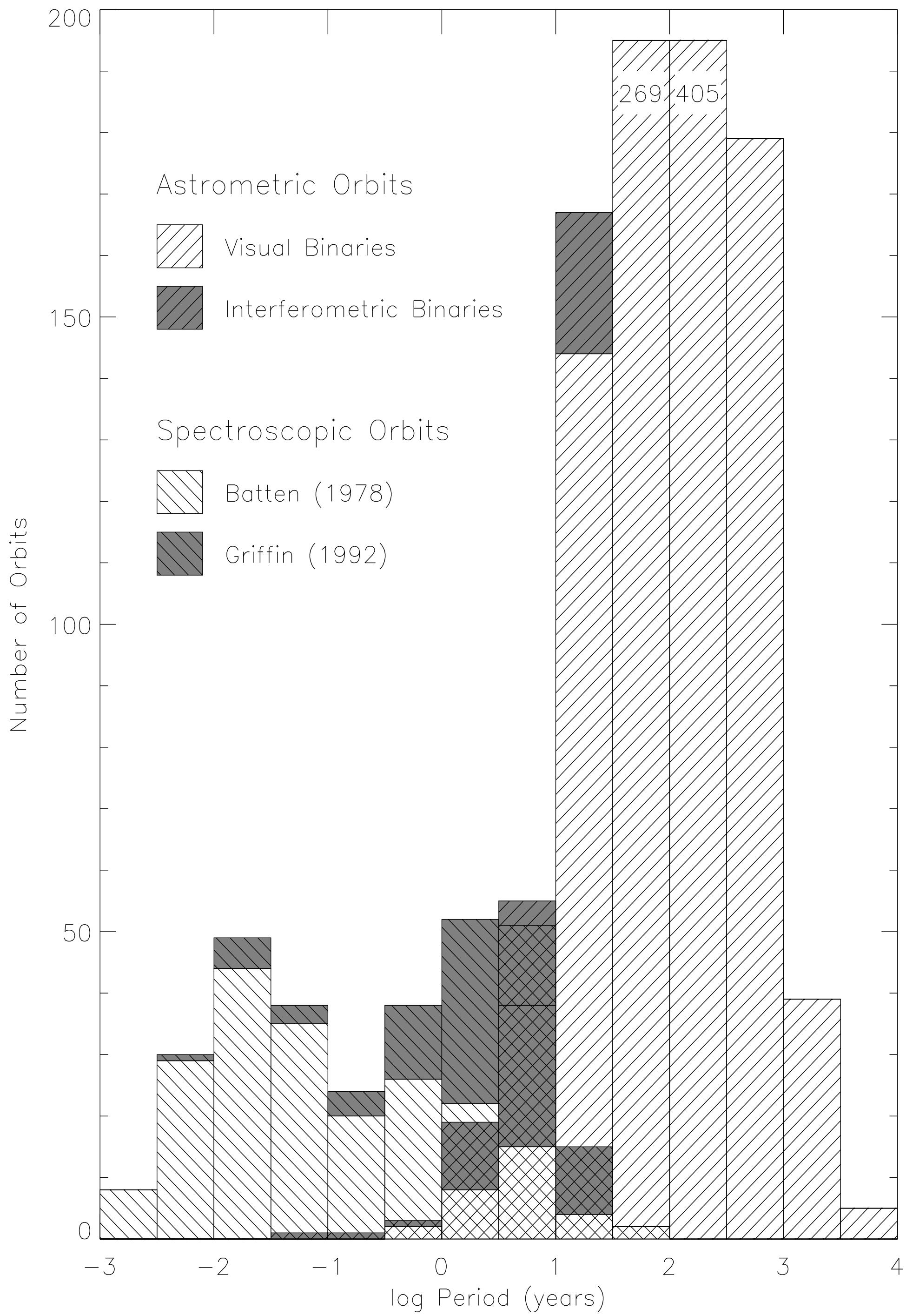

Figure 17.2: Same as Figure 17.1, with the addition of spectroscopic orbits published by Griffin as of 1992, as well as astrometric orbits of binaries discovered by interferometric techniques and tabulated at the USNO. These additional data are shown as shaded hatched regions in the histogram.

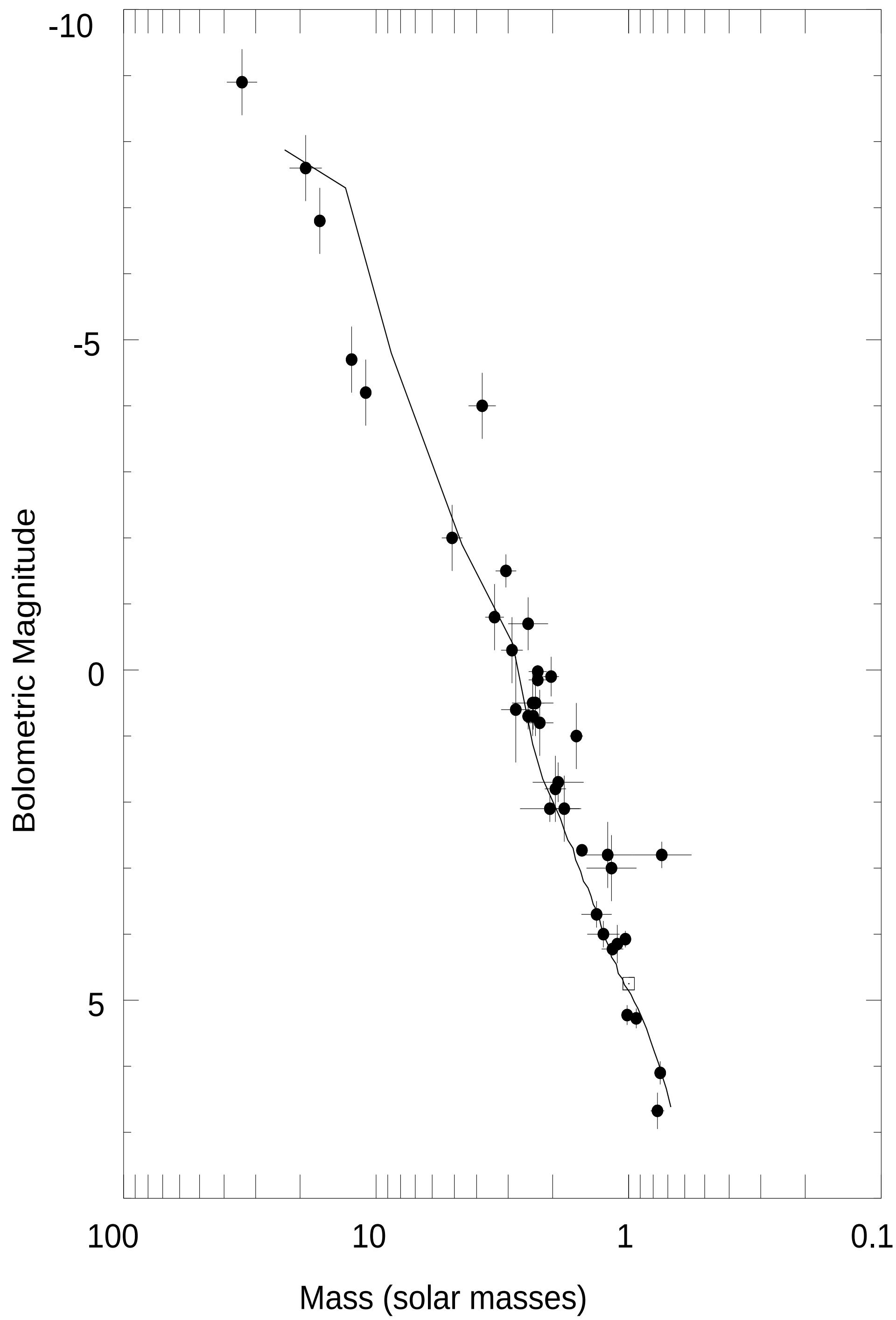

Figure 17.3: Mass–Luminosity diagram, from astrometric orbits defined primarily by interferometric observations (B. Mason, private communication).

17.2 Reason Two: Binaries as Yardsticks

Note that the above-mentioned combination of spectroscopic and astrometric orbital elements yields both a'' and a. From these two values we can immediately derive the binary's distance (this is often expressed as the "orbital parallax"). There are several advantages to this technique: First, no assumptions are needed regarding spectral type, interstellar extinction, etc. (as are needed with methods using stars' apparent magnitudes and colors). This technique works for stars even when standard parallax measurements fail (due to blended images of components). Finally, accuracy is not directly a function of distance.

17.3 Reason Three: Binaries and Stellar Evolution

The term "stellar evolution" is a broad one, and I will only touch on a couple aspects, by asking a few questions:

1. What role does duplicity play in stellar evolution?
2. Are ALL stars created in sets of two or more?
3. Do all stars have a choice—either companions or planetary systems? Can they have both?
4. Do stars of all spectral classifications show similar duplicity rate?
5. How does duplicity change with time? —i.e., once formed, how often are binaries dissociated?

The standard number we all hear is that about half of all stars are actually binaries; in other words, about two-thirds of the stars are members of binary or multiple systems. If a person glanced at the WDS (the Washington Double Star database, repository for essentially all binary star astrometric measurements ever made) they would think we have a pretty good handle on the binary star fraction. The WDS contains 450,000+ observations of $\sim$80,000 binaries, with 200+ years worth of data.

Duplicity surveys are incomplete, however, so the true numbers are not very well known! A quick example: through much of the 1980s the CHARA group attempted to make a speckle survey of the 9,000+ stars in the Bright Star Catalogue (see McAlister *et al.* 1987, 1993). In the process they discovered numerous binaries wide enough to have been seen by visual observers—in other words, naked eye stars never noticed before! Only about one third of the BSC has been surveyed, however, so there are probably dozens of as-yet undiscovered bright companions. Earlier in this decade Hipparcos (ESA 1997) found nearly 3,500 new binaries, many of them also observable visually. Samples of some specific stellar types—bright O stars, Be stars, B giants, a few white dwarfs—have also been surveyed by speckle, but much more is needed. I will return to this point at the end of this talk.

The problem is even worse than that, however. Just as one technique can't provide all the orbital information needed for mass determination, one technique can't make a complete survey for duplicity at all separations. For example, due to both theoretical and equipment limitations, speckle at a 4-m telescope can only detect binaries within the separation range ~30 mas to a few arcseconds. A survey using multiple techniques, however, is time- and telescope- and money-consuming. As a result, there have been very few thorough duplicity surveys. I will discuss this further in a moment. Let me return to the questions presented a moment ago and give you one tantalizing result.

Surveys of pre-main sequence (PMS) stars in young star-formation regions [for example, the Taurus–Auriga complex, age 0.002 Gyr, by Mathieu (1994); also other surveys by Ghez *et al.* (1992), Leinert *et al.* (1992), etc.] have found multiplicity rates roughly twice those of their older (~5 Gyr) solar-neighborhood counterparts. Patience *et al.* (1998) found that the multiplicity fraction in the Hyades (age 0.7 Gyr) was somewhere in between those of the PMS and older stars. A possible reason—Leonard (1995) has suggested that binary-binary collisions within clusters and associations eject stars, resulting in lower binary frequencies in clusters than in the initial stellar distribution.

A speckle survey of all O stars brighter than V=8.5 (Mason *et al.*, 1998a) found a much lower binary frequency for stars in clusters and associations compared to field stars, supporting Leonard's assertion. Just when do these ejections or other binary disruptions occur, however? Little information is known for that age gap from 0.7 and 5 Gyr. Mason *et al.* (1998b) surveyed ~200 solar-type stars, combining archival visual micrometry with speckle interferometry to survey the region from about 2 to 120 AU around each star. Chromospheric activity was used as an indication of age to segregate the stars into a couple different groups. Their findings: for a sample of 84 chromospherically active stars (age ~1 Gyr) they find a duplicity fraction of 18%. A sample of 118 less-active stars (average age ~4 Gyr) yielded a multiplicity fraction of 9%. Although intriguing, the samples are too small to draw many conclusions yet. More complementary data at both closer and wider separations are also needed.

17.4 Reason Four: Binaries in Other Guises

The effects of duplicity are not always obvious! Let me give you an example.

There are a class of variable stars called λ Boo variables, first recognized by Morgan in the early 1940s. As a class they are rather poorly defined—definitions vary from author to author—but are usually denoted as having weak metal lines (especially one Mg II line), while C, N, O, and S are nearly solar in abundance. Most but not all have moderate to high projected rotational velocities. The stellar types are rather uncertain, as well. Farraggiana and Bonnifacio (1999) find several published hypotheses:

1. Very young stars which have not reached the main sequence
2. Main-sequence dwarfs, with ages of 10^7–10^9 years, or
3. Quite old objects resulting from mergers of W UMa type binaries.

In other words, the stars have been narrowed down to either pre-MS, MS, or post-MS stars!

In collecting the available literature on λ Boo candidate stars, Farraggiana and Bonnifacio find evidence of duplicity for 1/4 to 1/3 of these stars, largely from speckle or Hipparcos observations. They hypothesize that most λ Boo stars may in fact be normal binary stars, and that the abundance anomalies are simply due to "veiling"—filling in of spectral lines by the other component's continuum.

How many other types of variable stars are thought to be binaries? I checked Sterkin and Jaschek's book *Light Curves of Variable Stars*. The results were surprising—some 40 variable classifications! Here they are:

- Eruptive variables:
  - ⋆ RS CVn — close binaries with H and K Ca II in emission
  - ⋆ IN(YY) — matter-accreting Orion variables
- Eruptive supernovae and cataclysmic variables:
  - ⋆ Novae — massive white dwarf/cool dwarf binaries — include fast, slow, very slow, recurrent types
  - ⋆ Nova–like systems — WD+WD, WD+MS, etc. — include AM CVn, AM Her, DQ Her, UX UMa, VY Scl systems
  - ⋆ Type I supernovae
  - ⋆ Dwarf novae or U Gem variables — include SS Cyg, Z Cam, SU UMa, and Z And or symbiotic stars
- Eclipsing variables:
  - ⋆ EA — Algol types
  - ⋆ W Ser systems — long-period Algol-like mass-transferring binaries
  - ⋆ EB — β Lyr types
  - ⋆ EW — W UMa types
  - ⋆ GS — have one or more giant components
  - ⋆ PN — one component is nucleus of a planetary nebula
  - ⋆ WD — have white dwarf component
  - ⋆ WR — have Wolf-Rayet component
  - ⋆ AR — AR Lac type detached systems
  - ⋆ DM — detached MS systems
  - ⋆ DS — detached systems with subgiant

  * ⋆ DW — detached systems like W UMa system
  * ⋆ KE — contact systems of early spectral type
  * ⋆ KW — contact systems of late spectral type
  * ⋆ SD — semi-detached systems

- X-ray sources — 9 categories of bursters, novae, pulsars

What can interferometry contribute to the study of these objects? Other speakers this morning will discuss many of these contributions—sizes and shapes of component stars, hot spots and dark spots, limb-darkening and other effects, eventually imaging of accretion disks or matter streams. "Simple" interferometry can yield other useful information as well. Consider a few examples which come to mind (there are MANY more!):

- Masses and distances—basic but essential information, obtained as mentioned in Reason 1. Note that these data can be obtained for other variables in "normal" binaries, as well.
- Knowledge of the orbital inclination gives the exact trajectory of one component during an eclipse. Coupled with photometric and spectroscopic data this may allow one to determine sizes and compositions of extended atmospheres, accretion disks, etc.
- Some longer-term variability is believed to be caused by orbital precession presenting us with different viewing angles of a close binary. Precise astrometry will allow us to measure these precessional changes.

17.5 Reason Five: Binaries as "Vermin"

Some people despise binary stars (poor misguided fools)! These are often people who need point sources for calibration or as guide stars for pointing satellites, etc. As I have been discovering since joining the USNO in the summer of 1999, the celestial reference frame is also of vital importance for guidance of aircraft and missiles. A jet airplane that uses a binary star as a reference point, may have huge navigational errors that arise solely from the changing position of binary's photocenter. As an example closer to most of our interests, guidance sensors on a satellite such as HST may be unable to lock onto a binary guide star, causing the satellite to waste time searching for another guide star or to just lose an observing cycle altogether.

Surveys for duplicity, then, are important from a technical, non-astronomical standpoint. Consider one example—SIM (the Space Interferometry Mission). This mission involves narrow-angle astrometry of target stars relative to a stable framework of grid stars. For SIM to succeed, it needs some 4,000 grid stars (plus an additional 2,000 backup stars)

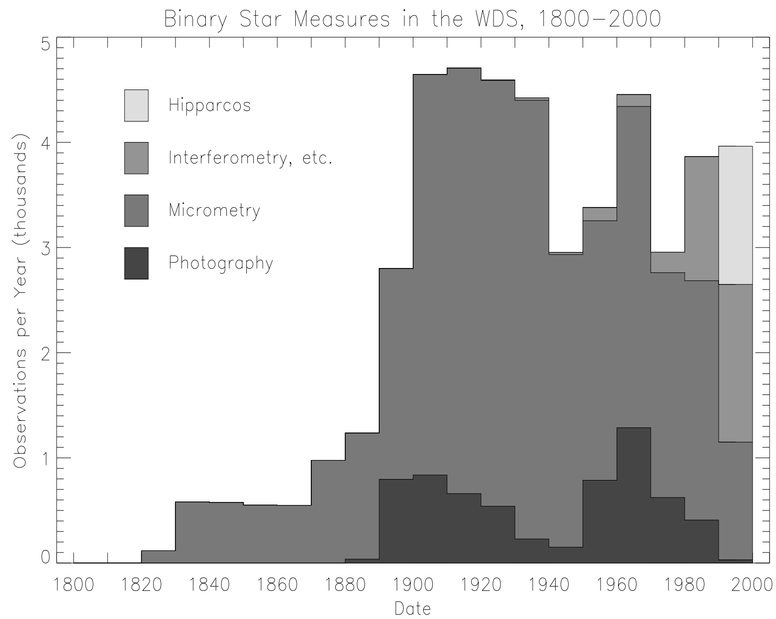

Figure 17.4: Number of binary star measurements per year from 1800 to 2000, as tabulated in the Washington Double Star database. Observations are categorized by observing technique and averaged by decade.

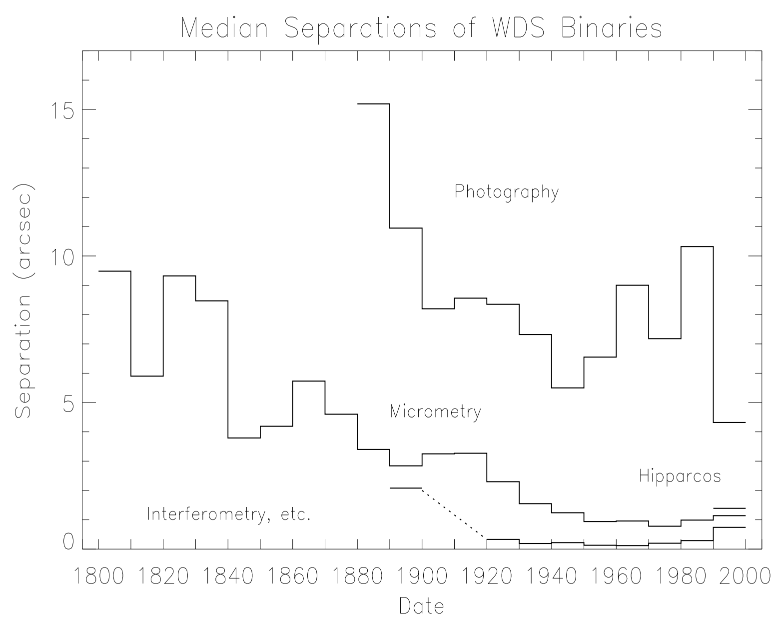

Figure 17.5: Median separation of binaries in the Washington Double Star database, 1800–2000. Observations are again categorized by observing technique and binned by decade. The first interferometric measurements were made by Schwarzschild in the mid-1890s; no further binary star interferometry was done until Anderson and Merrill's work in the early 1920s—hence the gap in the data.

distributed over the entire sky which are astrometrically stable at the 4 μas level over the 5-year lifetime of the project. Obviously, double and multiple stars must be avoided! The USNO has undertaken a project to observe 7,200 stars for duplicity, using a combination of techniques. After checks against the WDS for known doubles, CCD imaging by the USNO astrograph will search for wide pairs, speckle interferometry will look for pairs down to $\sim$30 mas, and an Fourier transform spectrometer currently under construction will look for the closest pairs. Some samples of stars will also be surveyed using NPOI, although this instrument will be limited to the brightest few hundred northern targets.

I should note that interferometry has a distinct advantage in duplicity survey work. Unless a system is double-lined, a single spectroscopic observation won't tell you if a star is single or double—you must make two and probably more observations and look for line shifts. However, unless that system contains a variable star (so Δm becomes too large), a single astrometric observation will usually tell you if the object has a companion within the separation regime accessible to the instrument.

Okay, there we have five reasons why binary stars are great! Let me end with a couple figures to illustrate the current state of affairs regarding binary star observations. The histogram in Figure 17.4 shows the number of binary star measurements obtained per year over the past two centuries. We can see, for example, that the observing rate has remained about constant throughout the 20^{th} century. At first glance this looks fine, until one considers how the number of astronomers has changed during this period! The major thing which I want you to notice, however, is the change in technique. Measurements made photographically or using filar micrometry have plummetted during the past couple decades, as older visual observers retired or died. High-resolution techniques have virtually taken over the field, with 70% of data obtained thus far in the 1990s coming from either Hipparcos or interferometry (almost exclusively speckle interferometry). I expect interferometry to become even more dominant in the next few years.

Figure 17.5 shows both good and bad news. Median separations have for the most part continually decreased for most of this century. The bad news, however, is that median separations for interferometric observations have increased significantly. The reason—little interferometry is now being done at large telescopes. The CHARA speckle effort, which used 4-m and later 2.5-m telescopes, has essentially ended. Virtually all speckle measurements being published now are those obtained at the USNO on its 26-inch refractor. The earlier histogram is rather misleading, then. Yes, interferometry is taking over binary star astrometry, but unless that astrometry can be obtained in significant numbers at larger telescopes or using multi-aperture arrays, many of the benefits of interferometry will not be realized.

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